dark energy

Why is the universe expanding faster and faster?

The answer may be a form of energy we almost can't imagine

By Karen Wright



But the universe that Newton and Einstein knew was a tame, stable place. The Milky Way was the only galaxy in town, and its stars seemed fixed in the firmament. The seeming stasis of the night sky had stumped Newton, and even a theory as powerful as relativity failed to explain it. So Einstein added an arbitrary term to his equations. Mathematically, it acted like a repulsive force spread smoothly throughout the universe. Where gravity pulled, he said, this force pushed back in equal measure. He called this fudge factor lambda, and eventually it came to be known as the cosmological constant.

Einstein never felt good about lambda, because he couldn't point to any theoretical or experimental evidence for its existence. Later in life he called it his greatest blunder. "Admittedly," he wrote, "[lambda] was not justified by our actual knowledge of gravitation." But Einstein's imagination was always more powerful than the knowledge of his day, and now, nearly a century later, his blunder is beginning to look like yet another stroke of uncanny genius.

In the last 75 years, astronomers have radically revised their conception of the cosmos. Edwin Hubble showed in 1929 that the universe was not static but expanding-it was getting bigger all the time, as if some primal explosion were driving its contents apart. That primal explosion came to be known as the Big Bang, and the expanding universe was its love child. For 50 years, Big Bang cosmology reigned.

Then, three years ago, light from distant, dying stars revealed that the edges of space are rushing away from one another at an ever-increasing rate. The cosmos, it seems, is not just grow-

ing but growing faster and faster. The bigger the universe gets, the faster it grows. Some ubiquitous, repulsive force is driving at the margins of space, stomping on the accelerator. And there are no red lights in sight. That mysterious propulsion looks a lot like lambda.

Today's cosmologists are calling this force dark energy: "dark" because it may be impossible to detect, and "energy" because it's not matter, which is the only other option. Despite the sinister connotations, dark energy is a beacon that may lead physicists to an elusive "final theory": the unification of all known forces, from those that hold the components of atoms together to the gravity that shapes space. Meanwhile the notion of dark energy has helped reconcile a puzzling suite of recent observations about the shape and composition of the cosmos.

In fact, the future of physics and the fate of the universe may ultimately depend on a kind of antigravity that has heretofore been a subject of mere conjecture. The experts think they know what role dark energy plays in the cosmos. Now all they have to do is figure out what dark energy is.

HUBBLE AND HIS FELLOW ASTRONOMERS DISCOVERED THE EXPANsion of the universe by observing that galaxies in all directions are moving farther away from one another all the time. He was able to track this movement through a phenomenon called redshift, in which visible starlight gets stretched out into longer wavelengths (toward the red end of the visible light spectrum) as it moves through expanding space. The amount of redshift depends on the rate of cosmic expansion and the distance of the observer from the galaxy.

Einstein, Newton, and most other physicists had assumed that gravity would put the brakes on expansion. But decades

THE UNIVERSE SPEEDS UP

Supernovas are extremely bright, dying stars. The image below is of a nearby supernova, SN 1994D, some 45 million light-years away. Because certain types of supernovas emit light of uniform intensity, astronomers began studying light from very remote supernovas to determine how much the universe is slowing in its expansion. Three years ago studies of supernovas 4 to 7 billion years old turned up a spectacularly surprising result: The expansion of the universe is speeding up. A supernova 6 billion light-years away (right)—shown blazing, then fading away—was among those studied.





after Hubble's breakthrough, astronomers were still trying to measure the assumed deceleration. The answer finally came in the late 1990s, from giant telescopes studying the light of stars dying in spectacular explosions called supernovas. Supernovas are among the brightest events in the cosmos, so they can be seen from very far away. Because light from the most distant supernovas must travel for billions of years to reach our telescopes, astronomers can look to its redshift for a historical record of expansion "I was

floored," Turner

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reaching back billions of years. At a meeting in Washington, D.C., three years ago, a team of researchers from the Lawrence Berkeley Laboratory showed that recalls. "Yet everything the light from very distant supernovas is fell into place. This was stretched out less than was predicted given the current rate of expansion. Apparently, the answer we'd been the universe expanded more slowly in the past than it does now. Expansion isn't slowing down as expected; it's speeding up. The finding was counterintuitive, and it was based on

brand-new methodology. But at the same time, a second group of space-telescope studies led by Brian Schmidt and Robert Kirshner of the Harvard-Smithsonian Center for Astrophysics came to the same conclusion.

"It seemed like we must have done something wrong," says Kirshner. "The cosmological constant had such a bad stink, you know? I mean, 'Einstein screwed up. What makes you

think you're gonna do any better?""

"I was floored," echoes University of Chicago cosmologist Michael Turner, recalling his first encounter with the evidence

at the Washington meeting. "Yet everything fell into place. This was the answer we'd been looking for."

IN PARTICULAR, TURNER WAS LOOKING FOR A WAY TO RESOLVE CONflicting results that were turning up in other experiments describing the state of the cosmos. One set of studies sought to determine the shape of the universe by considering the

density of matter in it. Einstein had shown that mat-

ter curves space in predictable ways, so that universes with different densities of matter will

have different shapes. His theories allowed for three shapes: negative curvature, in which the universe looks like a saddle; positive curvature, in which the universe is spherical; and flat, the most unlikely case, in which the overall density of matter doesn't warp space, and photons travel in straight lines. Flat space isn't two-dimensional; it just isn't curved.

Each shape corresponds to a density of matter denoted by the symbol omega. To create a flat universe, matter must reach so-called critical density,

which means omega equals one. In a saddle-shaped universe, omega is less than one; in a spherical universe, it's more than one. Astronomers have sought to determine the value of omega and distinguish among these geometries by measuring the way space bends beams of light. The light they like to measure isn't visible; it's microwave radiation left over from the Big Bang that glows at the farthest reaches of the universe. Distortions in that microwave signal can reveal the shape of the intervening space. In a saddle-shaped universe, distinct patches of the microwave background would look smaller than they're predicted to be. A sphere-shaped universe would magnify the patches of background radiation. In a flat universe, patches of background radiation would be closest to their predicted size.

Recent studies of microwave background radiation had hinted that the universe is flat. But last spring, data from balloon-borne instruments lofted over Texas and Antarctica supplied convincing evidence. Minute fluctuations in the radiation were the expected size. The most precise measurements available revealed that the shape of the universe is flat; it has the

critical density and omega equals one.

Unfortunately, these findings don't match results from inventories of matter in the universe. The density of matter can be inferred from its regional gravitational effects on light and on the evolution of galaxies. When astronomers use these methods to tally up the contents of the cosmos, all the people, planets, galaxies, and gases put together account for less than a tenth of the density predicted by the microwave background data. Even the most exhaustive surveys, which include exotic forms of matter only recently discerned, find just a third of the critical density. There's not nearly enough stuff to account for the flatness astronomers observe. Unlikely as it seems, says Turner, the universe seems to be made up mostly of empty space-a vacuum.

"And that finding," says University of Texas physicist Steven Weinberg, "could be regarded as the most fundamental discovery of astronomy."

Weinberg is a Nobel-prizewinning particle physicist who has spent most of his life describing theoretical forms of energy that haven't been discovered yet. The discrepancy between the microwave background and the matter surveys intrigued him, because he knew that energy can shape space just as matter does. A flat universe, or indeed a universe of any shape, could well be molded by both matter and energy. Einstein had recognized this possibility when he perceived that energy and matter are essentially equivalent—as in $E = mc^2$. Thus, he knew that energy could constitute the missing two thirds of the critical density.

And unlike Einstein, Weinberg and his fellow theorists had never quite given up on the old idea of the cosmological constant—some widespread energy loitering in empty space. As quantum mechanics matured through the middle of the last century, it began to make sense, in a wonky way, that the apparent vacuum might have some energy in it. Theorists had even named the hypothetical vacuum energy lambda, in honor of Einstein's goof. And they'd realized long ago that if energy in the vacuum exists, it has a repulsive effect—one that could cause a universe to accelerate.

But if some exotic form of repulsive energy does make up two thirds of all the stuff in the universe, it must be very weak. Otherwise its effects would have been obvious long ago. Whatever the mysterious lambda is, it must do its work only across great distances, on a cosmic scale.

That was the nature of Turner's epiphany in Washington three years ago. The light from remote supernovas showed that some unknown repulsive force was speeding up the expansion of the universe. And the microwave data and the matter surveys only made sense if such a force existed. All the evidence pointed to the presence of a kind of energy that so far had existed only on paper. As he was standing in front of a poster from the Lawrence Berkeley lab, Turner put all of the puzzling pieces together.

"The discovery of an accelerating universe was simultaneously the biggest surprise and the most anticipated discovery in astronomy," he says. It put dark energy on the map.

so the universe circa 2001 is flat, accelerating, and very nearly empty. And astronomers are happy, because a single entity with Einstein's imprimatur can explain all these attributes. But if the existence of dark energy has simplified researchers' understanding of the contemporary cosmos, it has also introduced plenty of complications. One has to do with the fate of the universe.

In the days before dark energy, astronomers believed that the end of the expanding universe would be dictated by the density of matter in it. Just as matter determined the curvature of space, it would also predict the way that space would expand and whether it would ever contract. Back when cosmic expansion was caused solely by the cataclysmic propulsion of the Big Bang, the gravity of matter was expected to eventually slow it down, maybe even stop it, maybe even reverse it. In short, density equaled destiny.

Based on that reasoning, astronomers proposed three mod-

els for the fate of the universe, each corresponding to a different geometry and density of matter. In each scenario, the gravitational attraction of all the matter in the universe tugs at the heels of the Big Bang's momentum like a tireless dog that's latched onto the leg of a running mailman.

If omega is less than one, the universe keeps on expanding forever, but at an ever-diminishing pace. That universe has the saddle shape and is called "open." If omega is more than one, the universal expansion slows and eventually reverses, collapsing in a cosmic crunch. That universe is spherical and "closed." In a flat universe, where the density of matter is exactly one, the expansion eventually slows very nearly to a stop but never actually reverses.

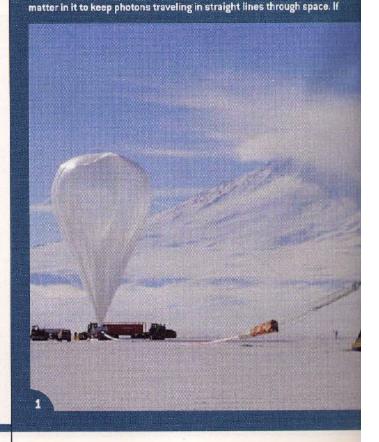
But if the universe is made up mostly of repulsive, ubiquitous energy rather than matter, then its ultimate fate isn't inscribed in its shape after all.

"We used to say that fate and geometry were connected," says Turner. "But that's only true if the stuff of the universe is matter alone. Once dark energy comes in, then destiny and geometry decouple. So you can have a closed

THE UNIVERSE

IS "FLAT"

(1) On December 29, 1998, Boomerang—Balloon Observations of Millimetric Extragalactic Radiation and Geophysics—set off, rising 23 miles above Antarctica. The balloon spent 10 days circling the south pole (opposite, map), covering 5,000 miles and surveying 3 percent of the sky. The gondola (2) carried a photon detector (3), which used sensors (4) cooled to -459.166 degrees Fahrenheit to record the microwave background radiation. The Boomerang data confirmed that the shape of the universe is flat. That means the cosmos has just enough



universe that expands forever and an open universe or a flat universe that collapses."

The only way to figure out the fate of the flat, empty, accelerating universe, says Turner, is to learn more about the dark energy that's impelling expansion. But even as they begin chasing down Einstein's notion of vacuum energy, physicists are having to grapple with problems that range from the numerical to the philosophical. For one thing, when they attempt to calculate the value of lambda, the theorists come up with a figure that is 120 orders of magnitude too big. Not 120 times too big—10¹²⁰ times too big. Fitting the known universe with a vacuum energy of that potency would be like filling up a water balloon with a fire hose.

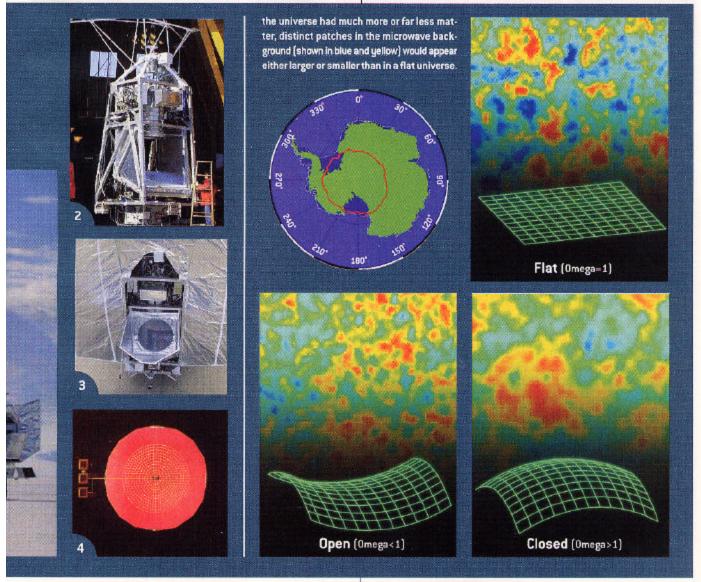
"It cannot possibly be correct," says Turner. "If it were correct, you wouldn't be able to see beyond the end of your nose, the universe would be expanding so fast." The size of the error has emphasized how poorly physicists understand certain aspects of gravity. "That is the biggest embarrassment in theoretical physics," adds Turner.

It gets even more embarrassing, because theorists can't ex-

plain why the densities of matter and energy are currently so close in value. Theoretically, either of those densities could be anything from zero to infinity, and their ratio could vary accordingly. The odds of their being within an order of magnitude of each other are very low. The precarious balance between matter and energy that exists today in our universe—one-third matter to two-thirds energy—seems as improbable as the static universe that Einstein struggled to describe. And some find that improbability especially suspicious, because a universe more dominated by dark energy would be inhospitable to life. The excess energy would prevent matter from clumping into galaxies, stars, and planets. Yet here we are.

The coincidence has driven even notorious skeptics like Weinberg to invoke, in exasperation, the anthropic principle. That much-maligned tautology states that human consciousness can question the terms required for its existence only in a world in which those terms have been met. If conditions were any different, no one would be here to ponder them.

"I don't like this kind of argument," Weinberg admits. "But I don't know of any other explanation that comes close."



THE UNIVERSE DOESN'T ADD UP

When light rays from distant galaxies pass a galaxy cluster closer to us, they bend in ways that can create spectacular "gravitational arcs"-the smudges of light in the image below. These arcs show the gravitational effects of the closer galaxy's enormous mass on light. Astronomers have also observed far subtler effects of this "gravitational lensing." When they imaged a patch of sky [right] and studied it closely, they turned up distortions (lower right) that betray the presence of unseen, "dark" matter.

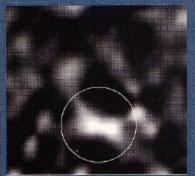
When astronomers use such studies to tally up all the matter in the universe, they don't find enough to explain how the universe is behaving. That's one reason they're thinking a force like dark energy is affecting how the universe expands.



Gravitational lensing in galaxy cluster Abell 2218



Near-infrared image



Dark matter distribution

The anthropic principle is anathema to most physicists. Some would rather propose a brand-new force in the cosmos than fall back on rhetorical sleight-of-hand. Paul Steinhardt of Princeton University, for example, has already ditched the cosmological constant in favor of a new category of dark energy that he calls quintessence. The fact that energy and matter have achieved a delicate balance is suspicious, he says, only if you assume there's no communication between the two. Steinhardt has proposed that repulsive energy senses the presence of matter and changes its strength or distribution to maintain a balance of densities. This energy could alter its properties over space and across time; unlike lambda, it wouldn't be distributed evenly, and it wouldn't remain constant.

"There was always logically the possibility of having such fields," Steinhardt maintains. "But there was no reason to invoke them, because they weren't required by any theory."

Now that there is, Steinhardt is hoping experimental physicists will turn up evidence of quintessence in minute fluctuations of temperatures in the cosmic microwave background. The MAP satellite scheduled for launch in June could be instrumental in detecting such signals. More detailed surveys of distant supernovas are also planned.

"Different dark-energy models will make different predictions about the evolution of the acceleration of the universe over time," says Saul Perlmutter, leader of the Lawrence Berkeley team. Perlmutter is championing a plan to study acceleration with a space-based telescope called the SuperNova/ Acceleration Probe, or SNAP. "We want to go back in history and find out when the universe went through its growth spurts."

Reckoning with dark energy will also spur attempts to define a quantum theory of gravity. Gravity is the only one of

the four known forces that has eluded description in terms of energy bundles called quanta. Physicists have already managed to bring the other three-the strong force, the electromagnetic force, and the weak force-into the quantum fold. But unlike those three forces, gravity typically operates on vastly different scales than quantum mechanics. "Gravitation governs the motions of planets and stars," Weinberg wrote in a recent review, "but it is too weak to matter much in atoms, while quantum mechanics, though essential in understanding the behavior of electrons in atoms, has negligible effects on the motions of stars or planets."

With the discovery of dark energy, the two worlds collide. In the acceleration of the universe may lie some clues to the behavior of tiny quanta of gravitational energy. Einstein's own theories of gravity allow it to have some sort of repulsive effect, so elucidating the nature of dark energy could hasten theorists on their way to a final theory unifying all the forces. That's why physicists scanning the furthest reaches of space with powerful telescopes suddenly seem very interesting to the physicists scribbling on the blackboards.

"It's very flattering for astronomers," says Harvard's Kirshner. "We have the attention of the high priests of our field."

But there's no guarantee that dark energy will serve up the eternal verities the high priests are hoping for. The unlikely balance of energy and matter and the strength of the vacuum energy may permit human existence through caprice, not necessity. Einstein himself knew well the hazards of counting on capricious nature. "Marriage," he once opined, "is the unsuccessful attempt to make something lasting out of an accident." Scientists who would seek permanent truths in the accelerating universe could be making the same mistake. X